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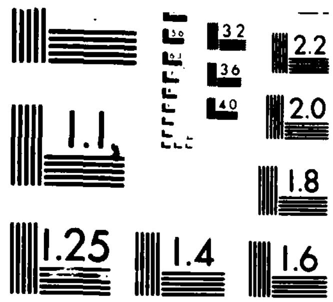
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MODIFICATION OF SEPARATING FLOW

By

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SUMMARY

The usual physical description of separation is that an adverse pressure gradient causes the deceleration of the low momentum flow near the surface. The result is a reduction of the velocity near the surface and a corresponding decrease in the shear stress at the wall as the slope of the velocity profile decreases. Finally, at some point, the shear stress at the wall vanishes and the flow separates. Downstream of this point the flow near the boundary reverses and a "dividing" streamline breaks away from the surface. Below this streamline the net flow is towards the separation point and above this streamline it is away from the separation point. This general type of flow field can generally be observed near the rear of bodies, in particular, flow separation occurs on the rearward part of bodies with a blunt shape.

A number of numerical calculations have been carried out in order to study the effect of transverse grooves on flow separation and incipient flow separation. These calculations are intended to throw light on the dynamics of the flow toward the rear of two- and three-dimensional bodies. In the most general case, body curvature should be included, and it would be necessary to calculate the flow past the body in a curvilinear coordinate system. This would be a massive undertaking for general geometries. In order to isolate the effect of the grooves on flow separation, apart from the effects of body curvature, it was decided to use planar geometry only.

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That is, the problem was taken to be the flow of an incompressible fluid in a two dimensional geometry past a plane wall. There is an externally imposed pressure gradient and a slot in the boundary. Calculations were carried out with the slot closed as well as open. The equations solved are the two-dimensional Navier-Stokes equations for the flow of an incompressible fluid. These are written in terms of the velocity, $\vec{u} = (u, v)$, and vorticity, ζ. These are

$$u_x + v_y = 0, \quad (1)$$

$$v_x - u_y = \zeta, \quad (2)$$

$$\zeta_t + u\,\zeta_x \;\; v\zeta_y = Re^{-1}\,(\zeta_{xx} + \zeta_{yy}), \quad (3)$$

together with appropriate boundary conditions. This set of differential equations is replaced by a corresponding set of difference equations. The difference equations used are of the compact form, that is only variables in a cell or on the boundaries of a cell are needed. This formulation has some advantages over more conventional difference schemes. In particular, it is trivial to use nonuniform grids as was done in these calculations. The nonuniform grids were, of course, used to give better resolution, in the near wall region and in the vicinity of the slot, than elsewhere.

Defining the difference, δ, and averaging, μ, operators by

$$\delta_x f_{i,j} \equiv (f_{i+1/2,\, j} - f_{i-1/2,\, j})/\Delta x \quad (4)$$

$$\mu_x f_{i,j} \equiv (f_{i+1/2,\, j} + f_{i-1/2,\, j})/2, \tag{5}$$

the Navier-Stokes equations are approximated by

$$\delta_x u^n + \delta_y v^n = 0 \quad , \tag{6}$$

$$\delta_x v^n - \delta_y u^n = \zeta^{n-1/2} \quad , \tag{7}$$

$$\mu_x u^n - \mu_y u^n = 0 \quad , \tag{8}$$

$$\mu_x v^n - \mu_y v^n = 0 \quad , \tag{9}$$

$$(\delta_t + (\mu_x u^n)\, \delta_x + (\mu_y v^n)\, \delta_y)\, \zeta^n = Re^{-1}(\delta_x \phi^n + \delta y\, \psi^n) \quad , \tag{10}$$

$$\delta_x \zeta^n = (\mu_x - \frac{1}{2} \Delta x\, q_x\, \delta_x)\, \phi^n \quad , \tag{11}$$

$$\delta_y \zeta^n = (\mu_y - \frac{1}{2} \Delta y\, q_y\, \delta_y)\, \psi^n \quad , \tag{12}$$

with $\quad q(\theta) \equiv \coth(\theta) - 1/\theta \quad ,$ (13)

$$\theta_x \equiv \frac{1}{2} u\, Re\, \Delta x \quad , \tag{14}$$

$$\theta_y \equiv \frac{1}{2} v\, Re\, \Delta y \quad . \tag{15}$$

A detailed derivation of these equations is given elsewhere (Gatski, Grosch, and Rose, 1982).

The geometry of the flow for which calculations were carried out was a solid boundary, both with and without a slot. There was an inflow boundary and an outflow boundary. At the "top" there was a freestream boundary.

At the inflow boundary the normal component of the velocity, u, and the vorticity, ζ, are given. In all of the calculations they were taken to be those of the zero pressure gradient Blasius boundary layer. Calculations were carried out for only one inflow Reynolds number. The Reynolds number, based on the free stream speed and the displacement thickness of the boundary layer was approximately 380. This was chosen so that the basic flow would be that of a stable laminar boundary layer. On the solid wall, and on the walls of the slot when it was taken to be open, the boundary conditions were taken to be that the normal and tangential components of the fluid velocity was zero. On the outflow boundary approximate boundary conditions

$$dv/dt = d\zeta/dt = 0 \quad , \tag{16}$$

were used. Finally on the free stream boundary on the "top" the tangential component, u, of tne velocity was specified along with an outflow condition

$$d\zeta/dt = 0 \quad , \tag{17}$$

on the vorticity. Specifying u as a function of the downstream distance, x, is equivalent to specifying the pressure gradient $\partial p/\partial x$. This is clear if one notes that in the free stream

$$p + \frac{1}{2}\rho\,(u^2 + v^2) = \text{constant.} \tag{18}$$

thus the specification of $u(x)$, and thus $v(x)$ through $\nabla.\vec{u} = 0$, $k \cdot \nabla x\,\vec{u} = \zeta$, effectively specifies $p(x)$. In fact, noting that $|v|/|u| \ll 1$,

$$\frac{1}{\rho}\,\partial p/\partial x \approx \frac{1}{2}\,\partial(u^2)/\partial x. \tag{19}$$

With these boundary conditions the flow is completely specified. However, there was one difficulty. If $u(x)$ on the "top" was given so that $\partial p/\partial x$ was unfavorable and separation occurred, one could not specify "outflow" boundary conditions on the downstream boundary because it was, in part, an inflow boundary. The proper inflow conditions on these sort of boundaries are not known, even in principle. In order to circumvent this problem, $u(x)$ or the "top" boundary was chosen so that the flow had a region of zero pressure gradient, followed by an unfavorable pressure gradient, then a region of zero pressure gradient. This resulted in the formation of a region of decelerating and near separating flow or the formation of a separation bubble on the boundary. In all cases, the flow at the outflow-boundary was that of an attached flow.

The solution algorithm for the set of difference equations is described in some detail by Gatski, et al. (1982) and will not be discussed further here. It will suffice to say that with the equations and boundary conditions described above, steady state solutions were obtained in all cases. This was true whether or not the boundary slot was open or closed.

However, in some cases many time steps were required in order to reach a steady state.

Calculations were carried out for a number of different cases. In all of these $u(x) = 1.0$ at inflow and for some distance thereafter. It is then reduced to a u_{min} and held at that value up to the outflow. Calculations have been carried out for a range of values of $u_{min} = 1.0$, to 0.70. This gave a range of adverse pressure gradients. In all cases the "opening" of a slot in the boundary significantly modified the flow in the neighborhood of the slot. If the slot were sufficiently deep, say greater than one boundary layer thickness, there was no significant increase in the drag due to the slot. However, the flow was locally, accelerated due to the presence of the slot and this had an important effect on the separating or near separating flow.

REFERENCES

Gatski, T. B., C. E. Grosch, and M. E. Rose, "A numerical study of the two-dimensional Navier-Stokes equation in vorticity-velocity variables," J. Comp. Phys. 48, 1-22, 1982.

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